



VIRTUAL TESTING OF COMPOSITES LAMINATE COUPONS

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1. MOTIVATION

2. SIMULATION STRATEGY

- Intralaminar failure: Continuum Damage Mechanics
- Interlaminar failure: Cohesive Crack Approach

3. VIRTUAL TESTING OF LAMINATES: EXAMPLES

- Low velocity impact
- Unnotched plain tension
- V-Notch shear test

4. VIRTUAL TESTING OF SINGLE LAMINAS

- In plane shear/transversal compression failure

5. CONCLUSIONS AND FUTURE WORK

Motivation

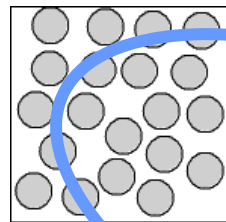
- Predicting the failure of materials is one of the oldest problems in engineering and one of the least perfectly solved. As a result, the burden of testing is immense to prove safety in structures upon whose integrity human lives depend (certification of an airframe structures requires $\approx 10^4$ tests of material specimens along with tests of components and structures up to entire tails, wing boxes, and fuselages).
- Recent developments in simulation strategies, increased computational power, and improvements in modeling tools are changing rapidly this scenario
- Nowadays it is possible to predict accurately the behavior until failure of composite coupon specimens and simple components through the application of bottom-up approaches.

Why virtual testing?

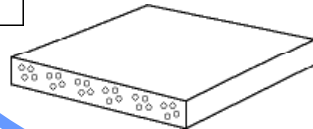
Certification Costs!

Reduce with virtual simulation tools
 New C/epoxy materials (3-4 M€)
 Total timeframe for certification (2-3 years)

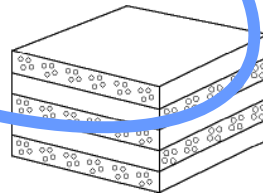
matrix & fiber



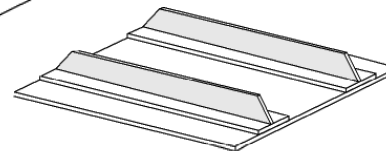
lamina



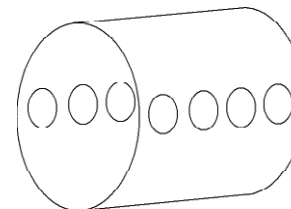
laminate



subcomponent



component



structure

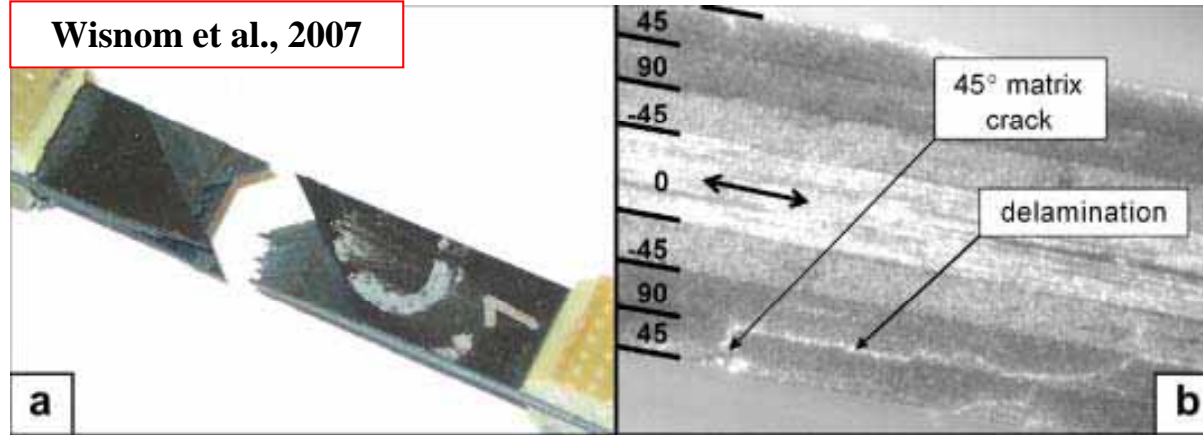


7TH FRAMEWORK PROGRAM MAAXIMUS
 (More Affordable Aircraft structure lifecycle
 through eXtended Integrated, & Mature
 nUmerical Sizing)) led by Airbus

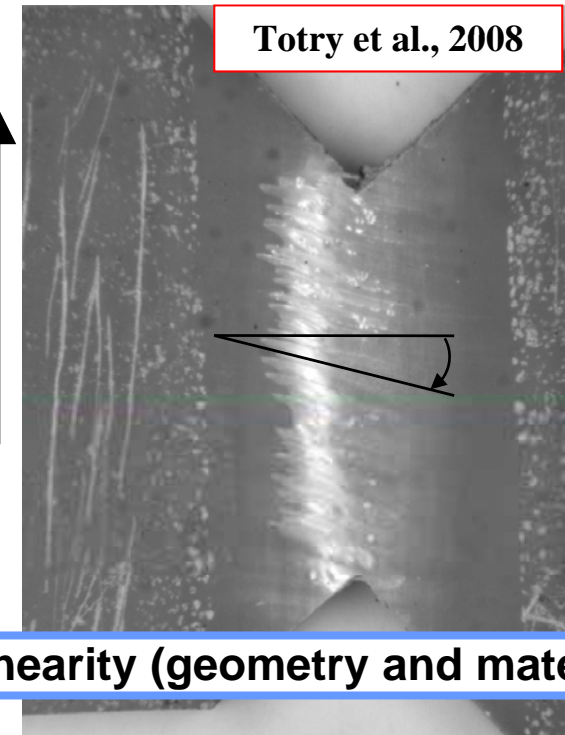
Simulation Strategy

Intralaminar failure (fiber failure, matrix cracking, interface decohesion)

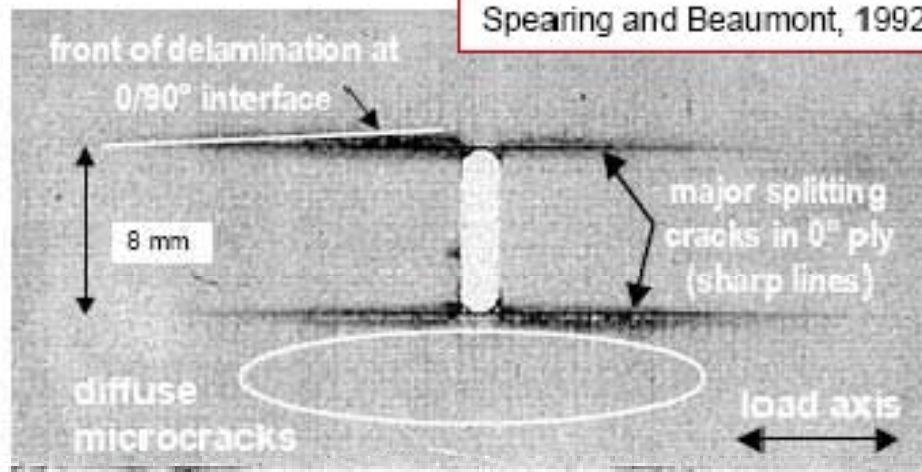
Wisnom et al., 2007



Totry et al., 2008



Spearing and Beaumont, 1992

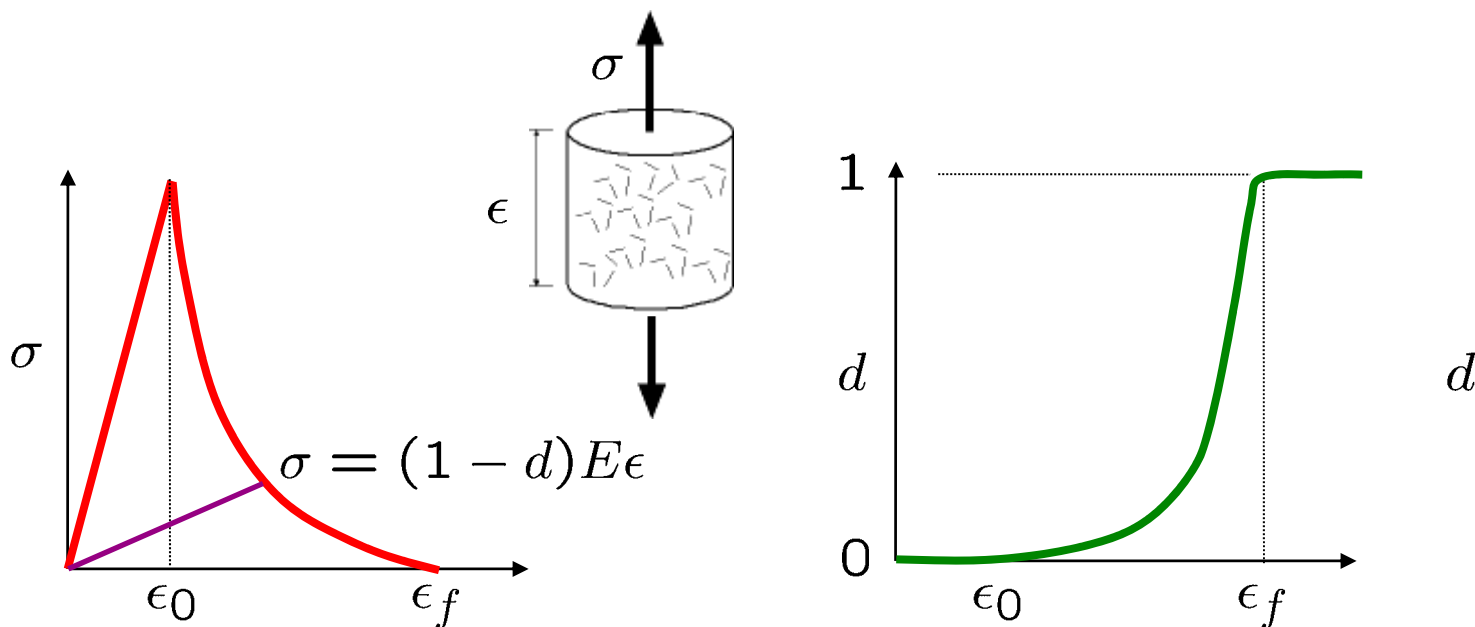


Interlaminar failure (delamination)

Non linearity (geometry and material)

Intralaminar failure: Continuum Damage Approach

- Continuum Damage Mechanics, Kachanov (1958), Chaboche (1981)
- Linear constitutive law between stresses and strains
- The influence of damage is addressed in terms of damage variables, d
- Evolution of damage variables is locally controlled by stress, strain, ...
- Anisotropic materials by MLT (Matzenmiller, Lubliner and Taylor, 1995)

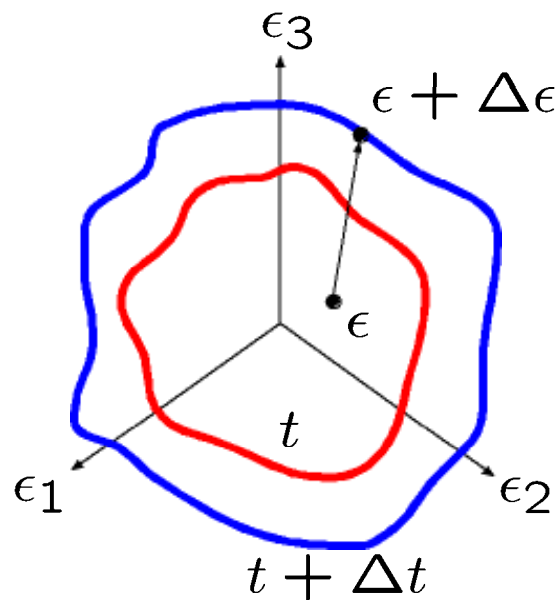


Intralaminar failure: Continuum Damage Approach

$$S(d_i) = \begin{pmatrix} \frac{1}{(1-d_1)E_1} & -\frac{\nu_{12}}{E_1} & -\frac{\nu_{13}}{E_1} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-d_2)E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{(1-d_3)E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-d_4)G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-d_5)G_{23}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-d_6)G_{13}} \end{pmatrix}$$

- CDM applied to orthotropic linear elastic solid $\sigma = S(d_i)\epsilon$
- 9 undamaged linear elastic constants (orthotropic material)
 $E_1, E_2, E_3, \nu_{12}, \nu_{13}, \nu_{23}, G_{12}, G_{13}, G_{23}$
- Damage variables d_i depend on damage mechanisms, stress, strain, ...

Intralaminar failure: Continuum Damage Approach



Failure surface given by the intersection of various smooth surfaces in the stress or strain space, which stand for the various failure modes:

- No damage $r_i = 1$
- Fully damaged $r_i = \infty$

$$f_i(\epsilon, r_i) = g(\epsilon) - r_i^2 = 0$$

The evolution of the failure surface given by the consistency condition

$$\dot{f}_i = 0$$

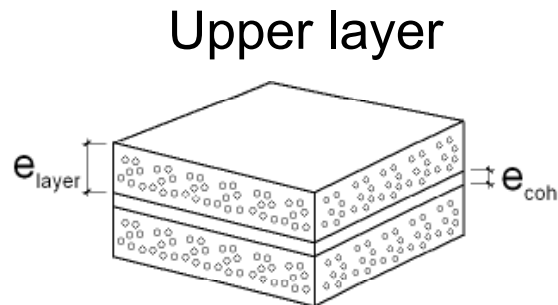
The evolution of the damage variables is given by:

$$d_i = 1 - \exp \left[\frac{1 - r_i^m}{m} \right]$$

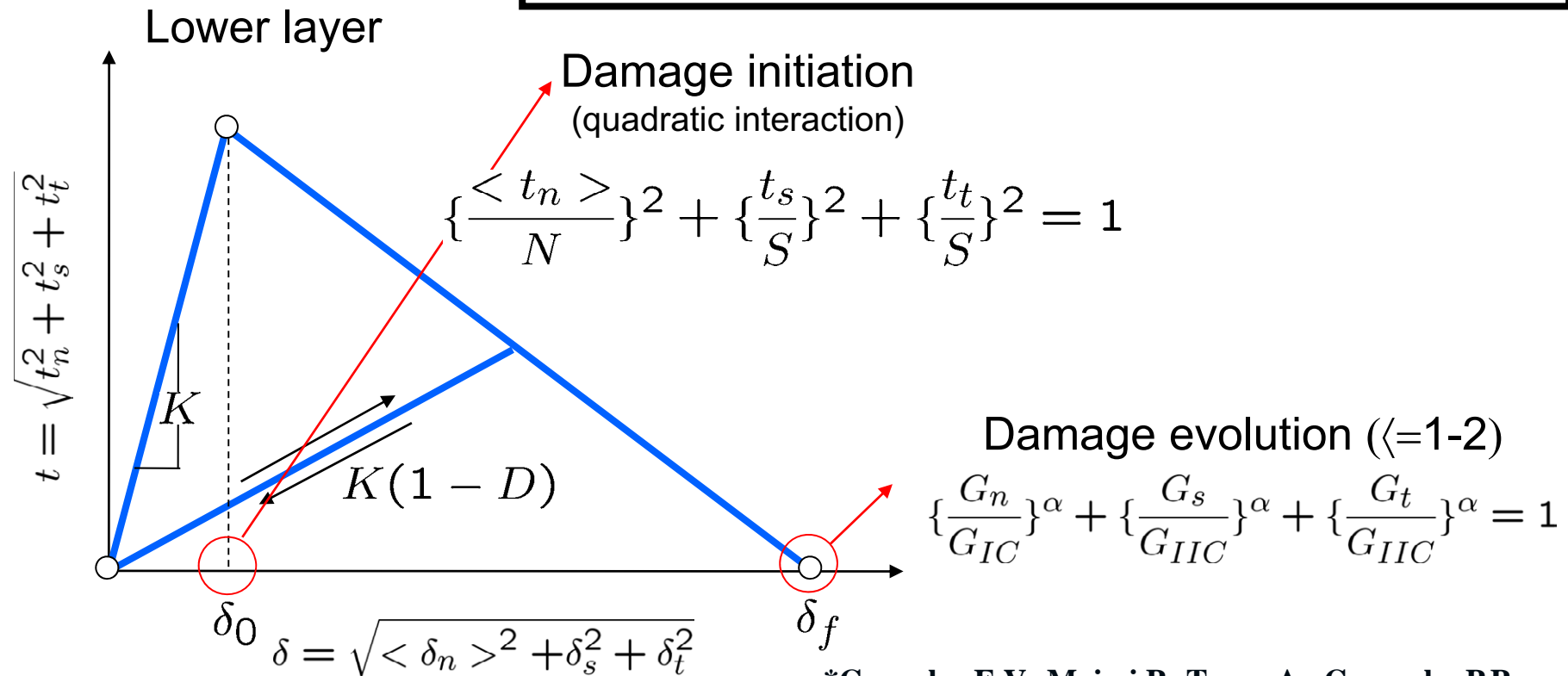
Implemented as a VUMAT in Abaqus/Explicit.

- Hashin failure surfaces for fabrics
- Larc03 failure criteria for unidirectional lamina

Intralaminar failure: Cohesive crack approach



- The interface properties are controlled by
 - Interface strength (normal N and shear S)
 - Interface fracture energy (G_{IC} G_{IIC})
- Cohesive element thickness $e_{coh} \approx 0.1 e_{layer}$
- COH Abaqus Element and VUMAT coded by UdG*



Virtual testing of laminates: examples

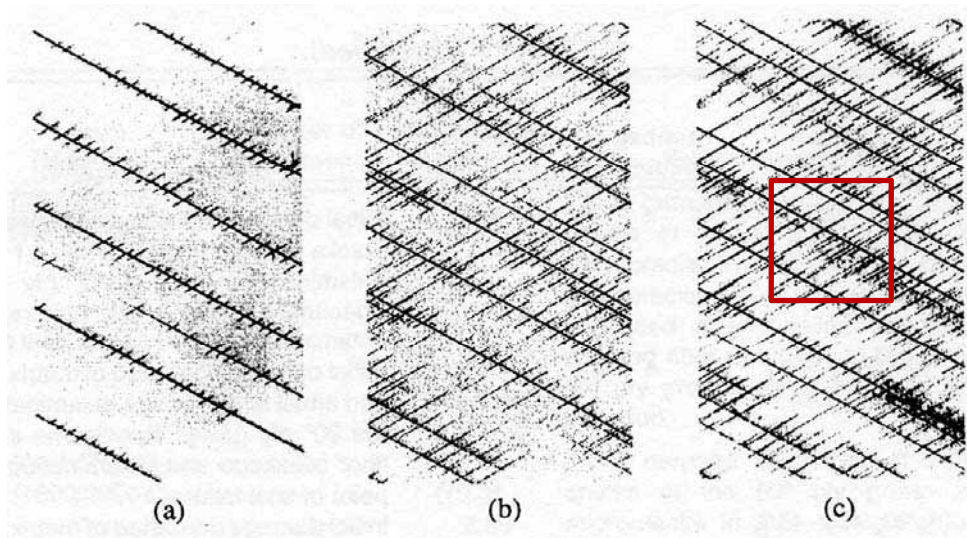
Unnotched plain tension

Plain tension of unnotched specimens for any arbitrary lay-up configuration

Evaluation of the failure mechanisms competition: intralaminar vs. interlaminar

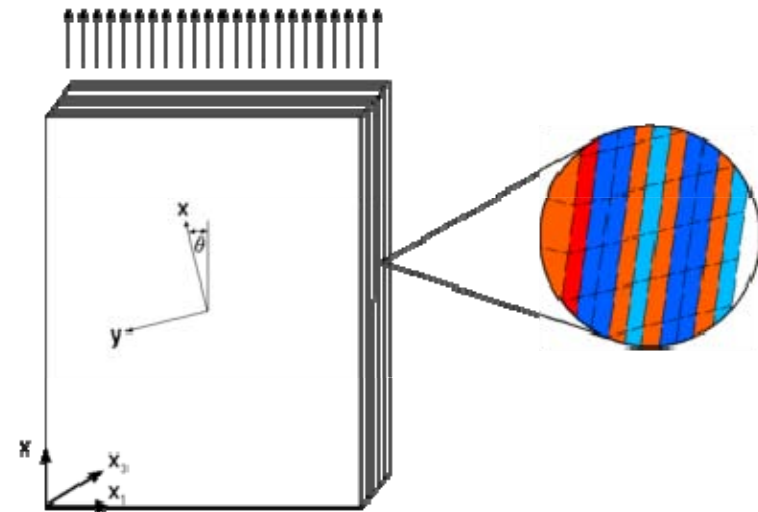
Preliminary study of the behavior of the composite material without edge effects

Matrix Crack-Induced Microcracking



X-Radiograph image obtained at increasing load levels showing microcrack propagation in a $[60_3/-60_3/0]_s$ laminate

Johnson and Chang, Journal of Composite Materials, 35, 2009

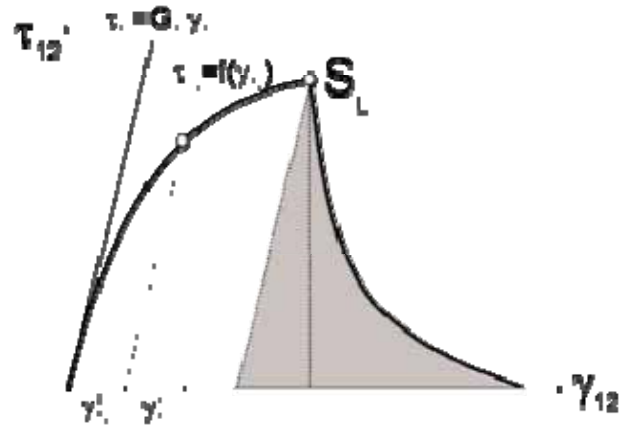




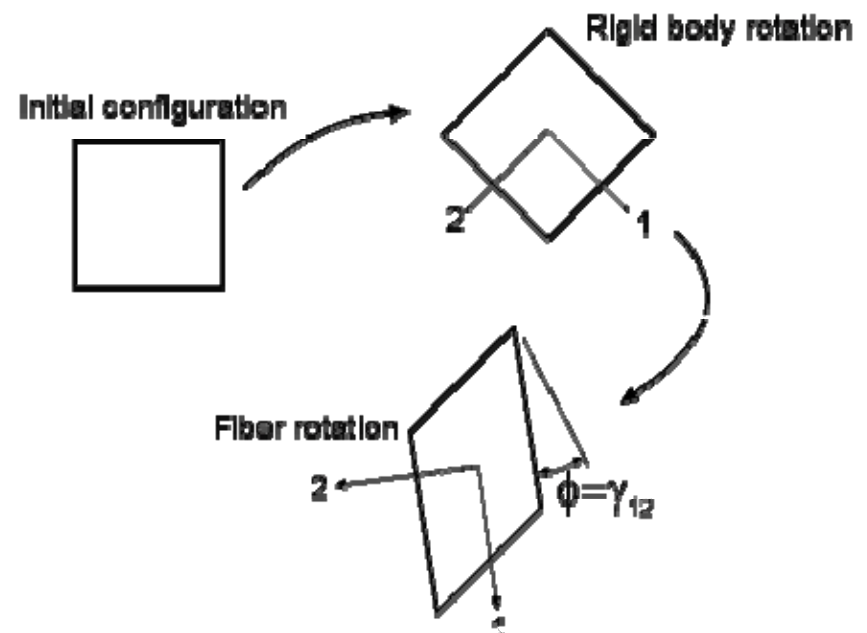
imdea
materiales



Introducing Shear Non-linearity (Pinho et. al.)



Effect of Fiber Rotation

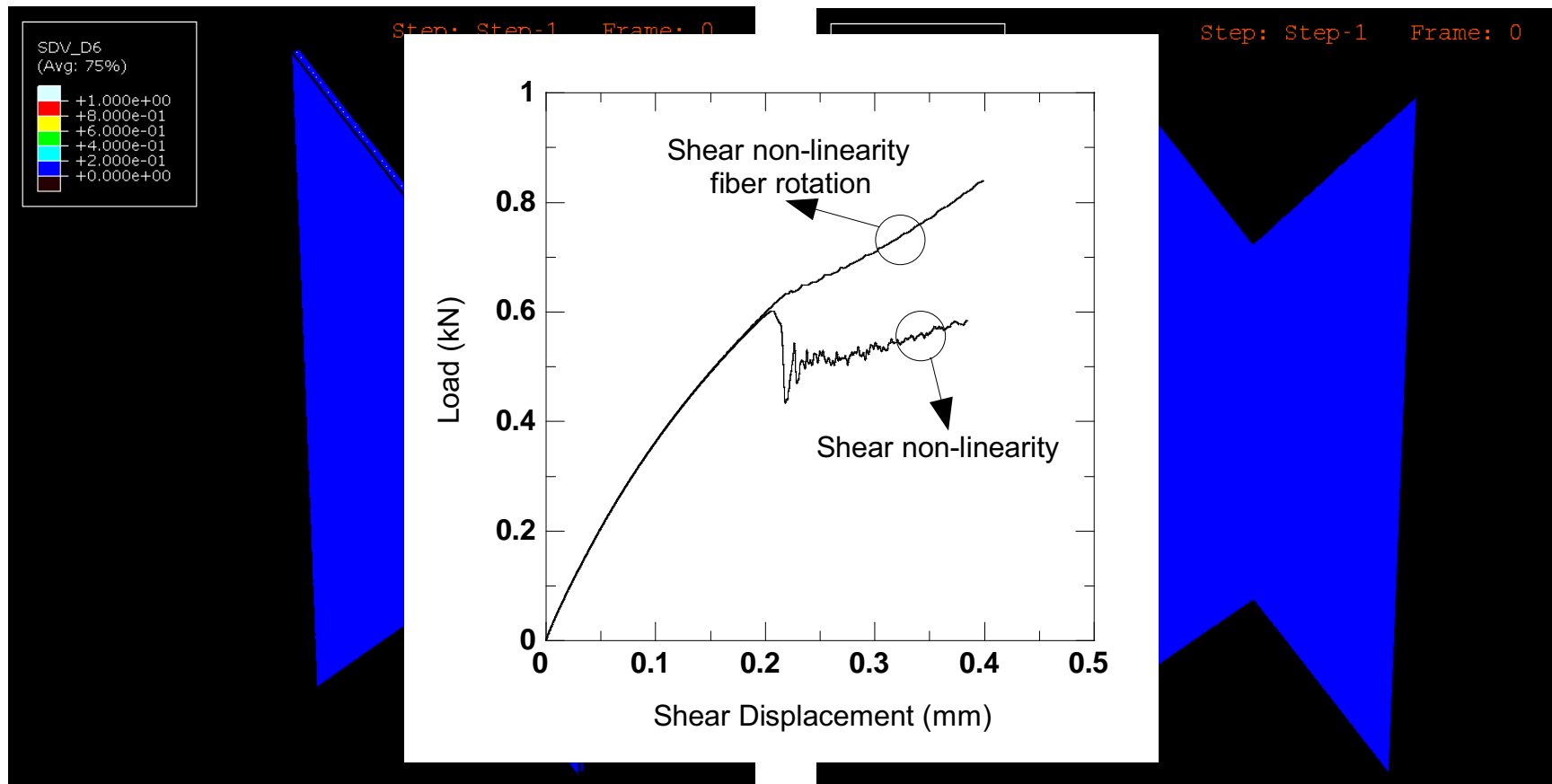


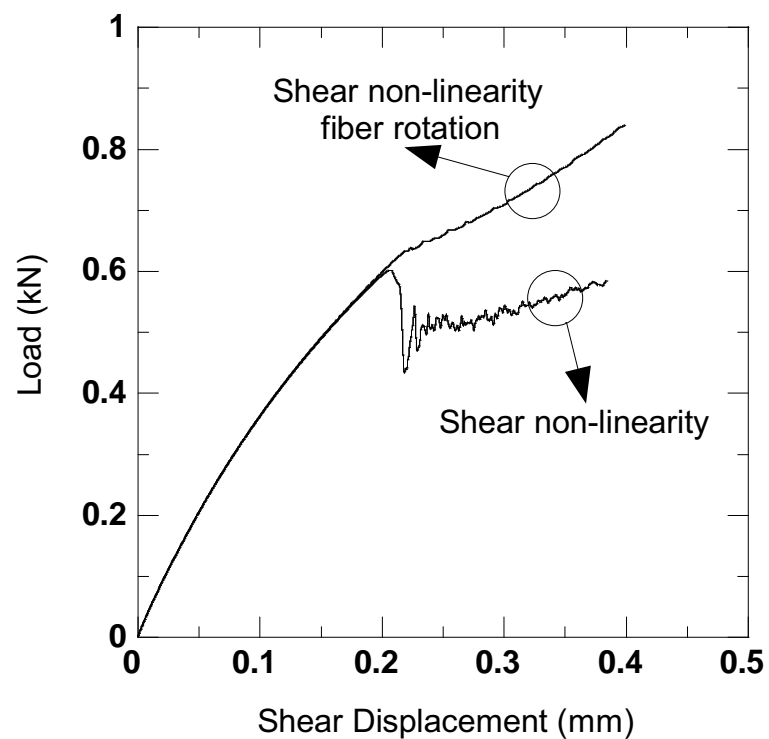
Preliminary Results including shear non-linearity and fiber rotation

$[0/90]_{2s}$ MTM57/glass ACG

d_6 Shear Damage Variable

Interface Damage Variable



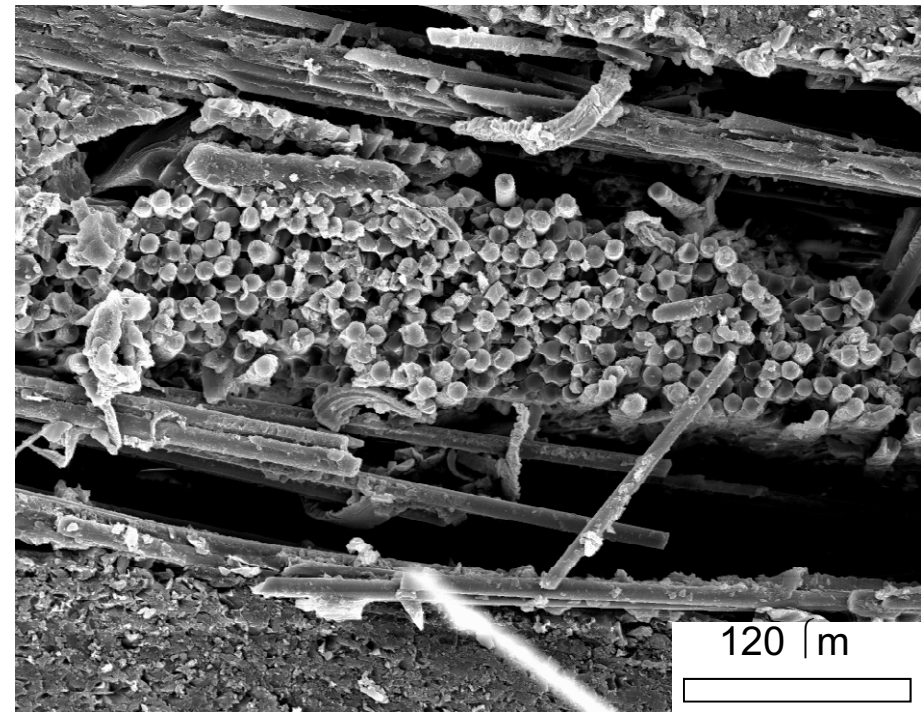
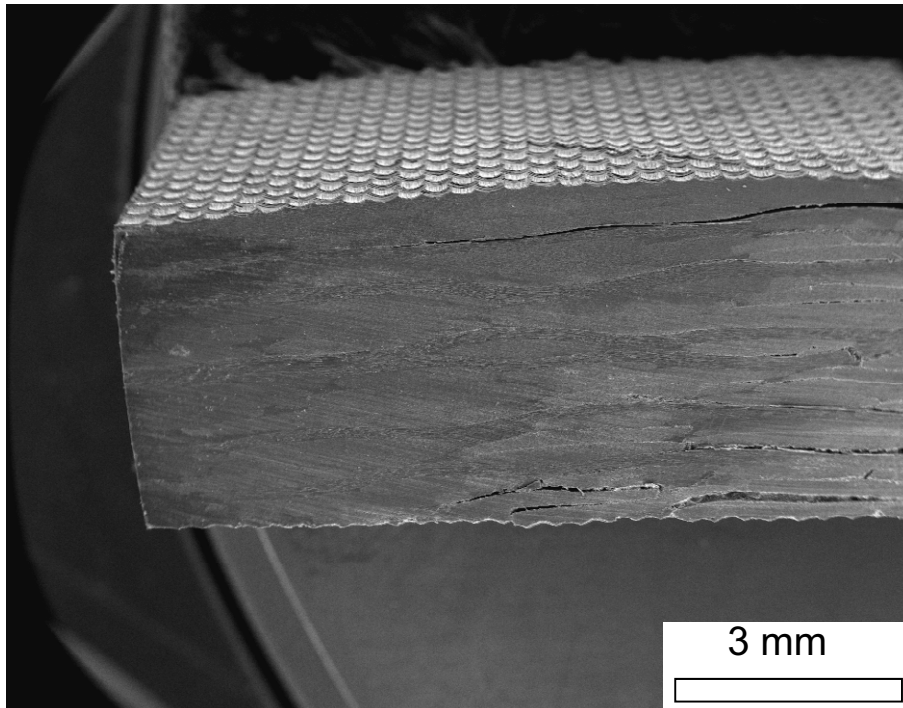


Example 1. At the lamina level

Example 2. At the laminate level

MATERIALS

- **Manufacturer:** Airbus Spain under Project BAITA.
- **Composition:** RTM6 epoxy resin matrix reinforced with G0926 5HS carbon fabric preforms.
- **Processing:** RTM technique followed by curing at 180 °C during 2 hours
- **Laminate thickness and fiber architecture:**
4.4 mm $[(45/0)_3]_S$ 5.9 mm $[(45/0)_4]_S$ 7.4 mm $[(45/0)_5]_S$



LOW VELOCITY IMPACT

Drop weight tower



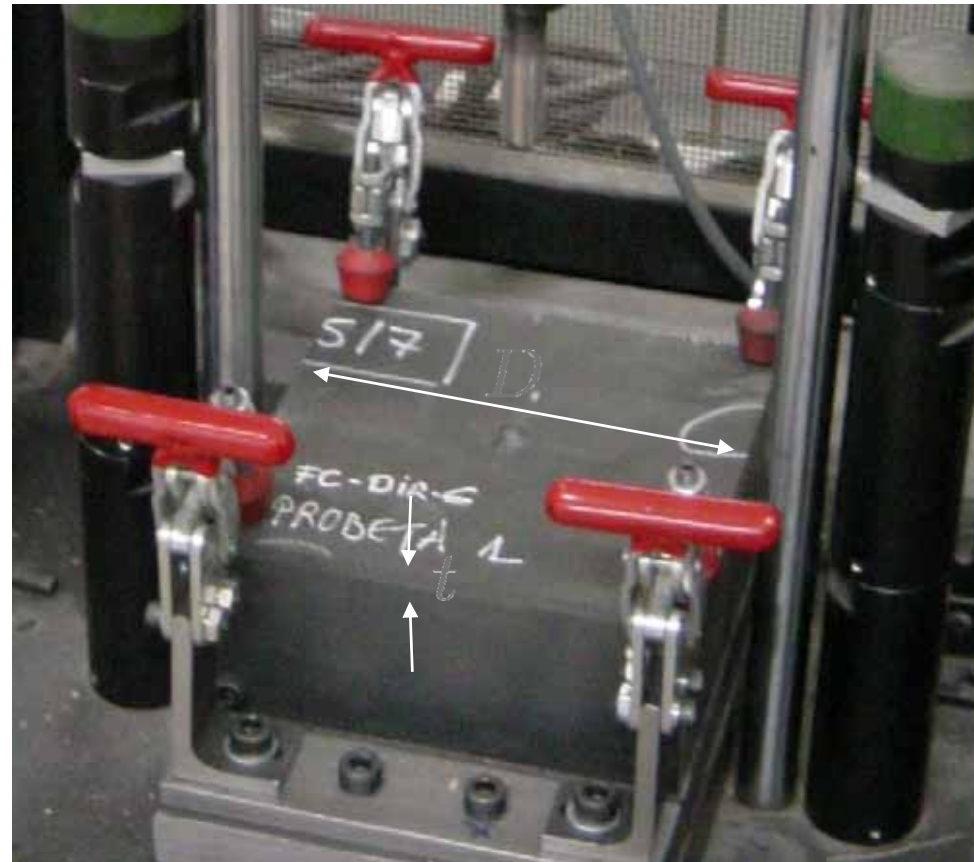
- Maximum speed: 4 m/s ($v = \sqrt{2gh}$)
- Maximum energy: 350 J
- Hemispherical impactor of 1/2 inch radius
- Accelerometer at the impactor tip

$$F(t) = ma \quad v(t) = \int_0^t a \, dt \quad \delta(t) = \int_0^t v \, dt$$



LOW VELOCITY IMPACT

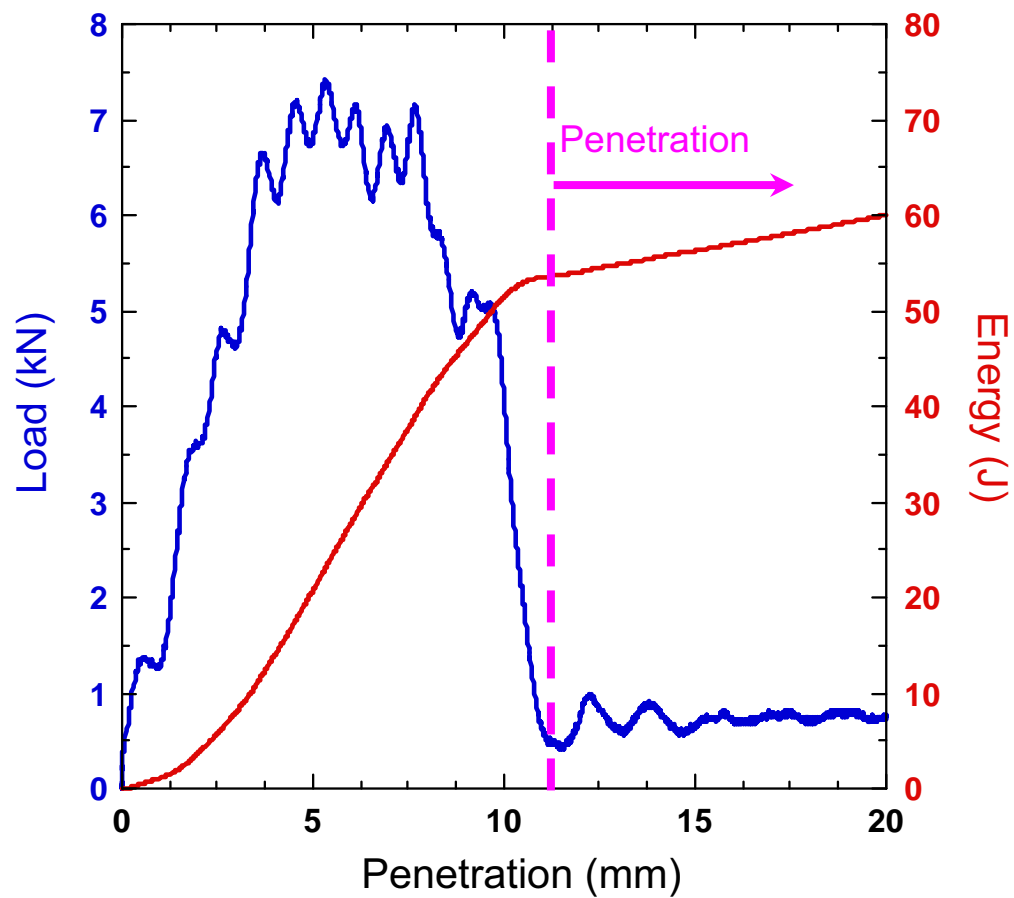
Specimen geometry



- Simply supported square plates of 145 x 145 mm
- Plate thicknesses: 4.4 mm, 5.9 mm, 7.4 mm
- Four impact tests for each thickness (2 without penetration and 2 with penetration)

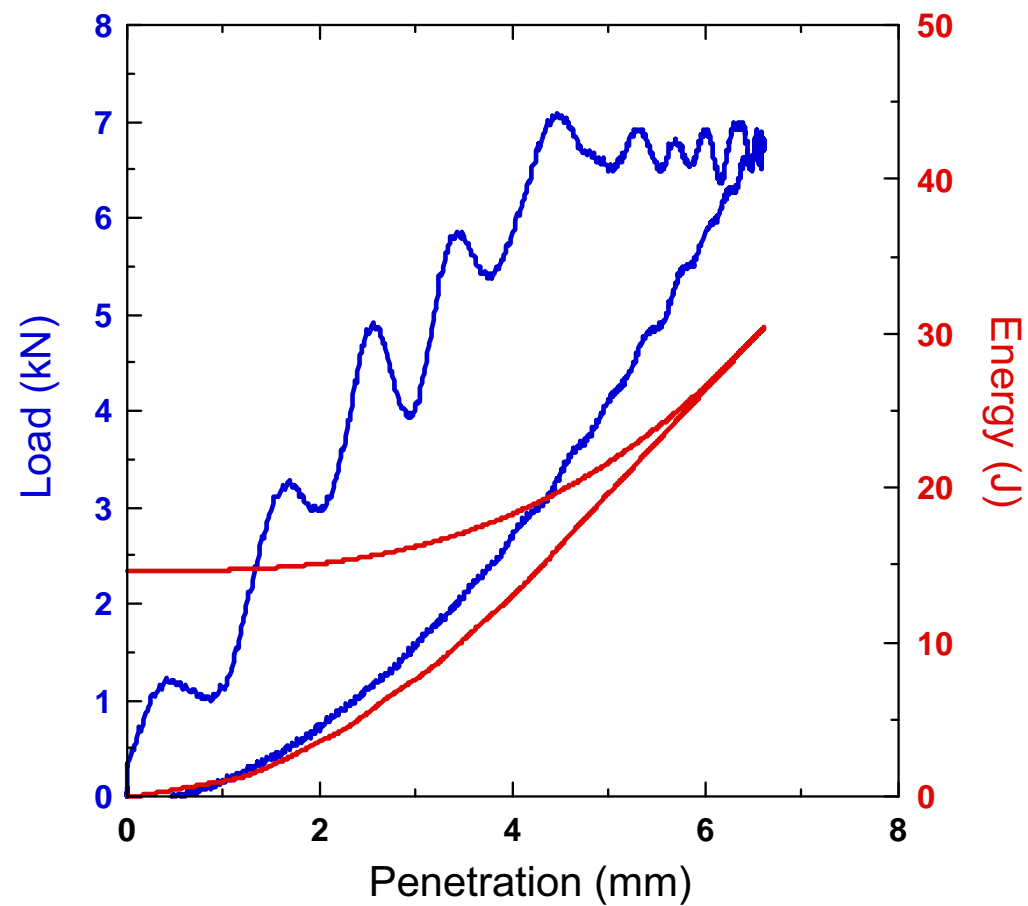
LOW VELOCITY IMPACT

Thickness 4.4 mm, $[(45/0)_3]_S$
incident energy 94 J



LOW VELOCITY IMPACT

Thickness 4.4 mm, $[(45/0)_3]_S$
incident energy 34 J



- Virtual mechanical testing of composite structures until failure can be carried out owing to the recent developments in multiscale modelling strategies.
- Bottom to Top strategy:
 - Intralaminar failure criteria and damage evolution through computational micromechanics. (2D and 3D solid and cohesive elements)
 - Coupon testing using cohesive elements (interlaminar fracture) and damage continuum mechanics (intralaminar failure). (3D solid and cohesive elements)
 - Component testing through structural analysis using micromechanical models for the homogenized laminate behavior. (3D continuum shell and cohesive elements)
- These virtual experiments open revolutionary opportunities to reduce the number of costly tests to certify safety, to develop new materials configurations and to improve the accuracy of failure criteria.